Invited Paper

A Computer Model to Differentiate Skidder and Cable-Yarder Based Road Network Concepts on Steep Slopes

Hans R. Heinimann[1]

Swiss Federal Institute of Technology, Section of Forest Engineering, ETH-Zentrum HG G 23, CH-8092 Zurich, Switzerland.

Road spacing on slopes depends on the underlying off-road transportation technology. One major decision in road network planning is to determine under what terrain conditions ground- or cable based extraction systems should be applied. The present investigation aims to develop a road spacing model for steep slope conditions and to implement a total cost model for skidder and cable-yarder based road network concepts. The study analyzes transportation and road geometry to specify the relationship between road density, slope gradient, and road spacing. Production functions for skidder and yarder-systems make it possible to derive transportation cost as a function of road density and slope gradient. A total cost function integrates road building cost, harvesting strategy, and production economics to derive optimal road density for the two network concepts. The difference between the cost levels at optimum road density is an indicator for differentiating cable and skidder-based extraction systems. The model was implemented as a Visual Basic add-in for Microsoft Excel spreadsheet software. This flexible approach makes future adaptations and changes very easy due to the modular concept. The validity of the model is limited to the production functions of the underlying off-road transportation technologies. Future work needs to develop production functions for the state-of-the-art technologies and to improve the road building cost model.

Key words: ground-based, optimization model, road network concepts, road spacing, skidder-based, total cost function

The layout of a forest transportation network is a decision that commits technical feasibility of off-road transport and harvesting cost for a long time. In flat terrain ground-based technology is the predominant approach to design forest harvesting systems. On steep slopes cable-based and aircraft-based technologies are often advantageous alternatives. One of the most important problems of transportation planning in mountainous terrain is where to use ground-based, cable-based or aircraft-based extraction concepts.

Optimizing road spacing is a problem in forest transportation planning which dates back to the classical work of Matthews (1942). Almost all the scientific work treating road spacing was carried out for flat terrain conditions considering specific off-road transportation technologies. In steep terrain Abegg's (1988) investigation seems to be the only attempt to differentiate ground- and cable based transportation concepts. An analytical approach formulating road spacing models for steep slope conditions is still missing. Such an approach would be very important to evaluate different harvesting situations. Deriving the optimal concept may restrict the search for a spatial feasible solution to the most sensible idea.

The present investigation aims (1) to develop an analytical road spacing model for steep slope conditions, and (2) to evaluate the model for specific harvesting situations. Landings are omitted because they are not relevant for European conditions. The model evaluation focuses on silvicultural and technological circumstances in Central Europe, but could easily consider conditions in other regions. The paper gives first a survey on previous work about road spacing models, then analyzes the new steep slope model and finally evaluates it for a case application.

Background

1 Transportation theory

Transportation theory gives the theoretical framework for road network geometry and its functional relationship to extraction (skidding or yarding) distances. Matthews (1942) was the first to formulate a two dimensional model with straight-line even-spaced roads. Assuming that the logs move on the shortest path to the nearest road the mean yarding distance is one quarter of the road spacing distance. This very simple relationship was also used in the first European study on road spacing (Soom, 1950) and is still the basis of recent investigations (*i.e.*, Clark *et al.*, 1997; Howard and Tanz, 1990; Peters, 1990; Thompson, 1992). Segebaden (1964) refined the road spacing model taking into account that (1) irregular stochastic networks may occur in reality, and (2) that off-road transportation follows a winded path that is not perpendicular to the road. To consider the first fact he introduced a network correction factor that may be estimated for specific road networks using a sampling system. An additional correction factor considers the increasing skidding distance due to the winding effect that Lussier and Tardiff (1964) called factor of sinuosity. Suddarth and Herrick (1964) presented a theoretical approach as well as a procedure to estimate the effective extraction distance for any geometric harvest setting. Segebaden's approach was used in most of the European studies on road spacing (*i.e.*, Abegg, 1978, 1988; Sanktjohanser, 1971).

Baldwin *et al.* (1987), Bowman and Hessler (1983), Peters (1990) and Thompson (1992) used two or more classes of roads laid out in perpendicular nets. In those cases transportation takes place in several stages. First, from the stand to

[1] Professor of Forest Engineering.

the second class road, then on the second class road to the first class road and finally the haulage on the first class road. Howard and Tanz (1990) investigated multi-stage off-road transportation on slopes. However, in all the investigations the basic relationships between extraction distance and road spacing was calculated from Matthews' model. Under mountainous conditions several classes of transportation lines are usual (*e.g.*, truck roads + cable roads; truck roads + skid roads). However the assumption that the two classes of transportation lines are perpendicular is not valid on steep slopes because of the limited gradient of roads. Abegg (1988) investigated this effect empirically, but did not derivate analytical relationships.

In all investigations on optimal road spacing the road network geometry was based on a two-dimensional model using the functional relationships of Matthews (1942) and Segebaden (1964) to calculate average extraction distance. The three-dimensional "real" situations on steep slopes has not been considered up to now.

2 Optimization of road density

Matthews (1942) was the first to define a total cost function for calculating optimal road spacing. The main components of all road spacing optimization models are (1) a procedure to calculate road building costs, (2) a procedure to calculate production (extraction) cost as a function of road spacing, and extraction distance respectively, and (3) functional relationships considering indirect cost (*i.e.*, cost for setting-up and taking down of cable yarders; Abegg, 1988) or overhead cost (Thompson, 1992). All the cost elements have to be transformed to a common unit of production output such as harvested volume or harvested area. The main problem in all total cost models are the productivity models of the technology used to estimate cost for off-road transportation. Therefore a total cost model is only valid for one specific technology. Bowman and Hessler (1983) and Sanktjohanser (1971) mentioned that on steep slopes a mix of ground-based and cable-based technologies are used in a specific area resulting in quite different characteristics and costs. Abegg (1988) therefore tried to estimate the amount of each technology as a function of slope and road density using empirical values. His total cost function considered the set of technologies used in a specific harvest setting and allowed to determine optimal transportation strategy (ground-based, cable-based) on steep slopes. He used empirical data to estimate the effect of increasing slope on cost such as a relationship between road building cost and slope.

Up to now an analytical approach to quantify the relationship between ground slope and road building cost is still missing while indirect cost are treated differently in the calculation of optimal road spacing (see Thompson, 1992).

Model Development

1 Problem statement

Figure 1 represents an idealized model of road network layout on steep slopes. It assumes a plane of infinite expansion and constant slope η; parallel first order transportation lines

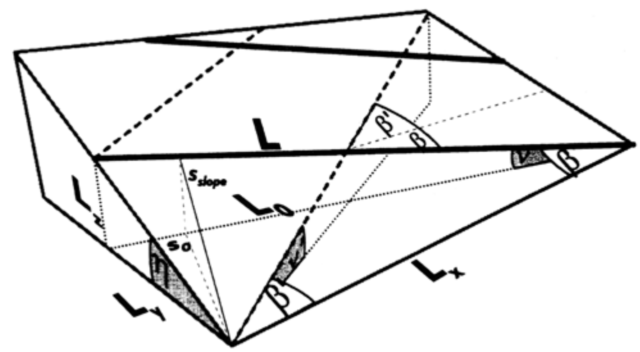

Fig. 1 Three-dimensional model of a transportation network. The model takes into account two classes of transportation lines: (1) truck roads, (2) skid roads and cable roads respectively. L, length of road segment; s, road spacing; η, slope grade; v, maximum grade of transportation line.

(truck roads) that are even spaced; parallel second order transportation lines (skid roads, and cable roads respectively), also even spaced; the arrangement of the two classes of transportation lines in a way that the angle of intersection is as close as possible to 90 degrees; limited maximum grades of first and second order transportation lines (angles η and η' respectively) resulting in acute-angled intersection on steep slopes; measurement of all areas and distances in the horizontal x-, y-plane (*i.e.*, length or road segment L_0 or road spacing s_0), according to the rules of surveying. The block model and the symbols will be used to analyze the geometric relationships of network and road geometry as a function of slope grade. The main problem to solve is to define a total cost function taking into account the geometrical properties of network layout as well as different off-road transportation technologies.

2 Conceptualization

Formulating a road spacing model consists of expressing all relevant costs as a function of road density and road spacing. Different off-road transportation concepts require different models because of the miscellaneous mathematical representation of specific off-road transportation technology. Designing such a model is a complex task that needs special design practices. The most promising approach is hierarchical decomposition known from general systems theory resulting in a modularization of the overall problem. Figure 2 represents the concept formulation taking into account the main principles of modularization. A module should have a simple interface for communicating on the outside. It should put together tasks of the same kind, and make it possible to be integrated in a whole system. The module "transportation geometry" defines the relationship between extraction distance and road density, whereas the module "road geometry" gives functions to quantify the excavation volume during road building. "Production economics" is a key module consisting of (1) productivity models for specific off-road transportation technologies (skidding, yarding), and of (2) system cost estimation. The module "building economics" identifies the cost of roads as a function of ground slope and road standard. "Harvesting strategy" outlines the silvicultural system by

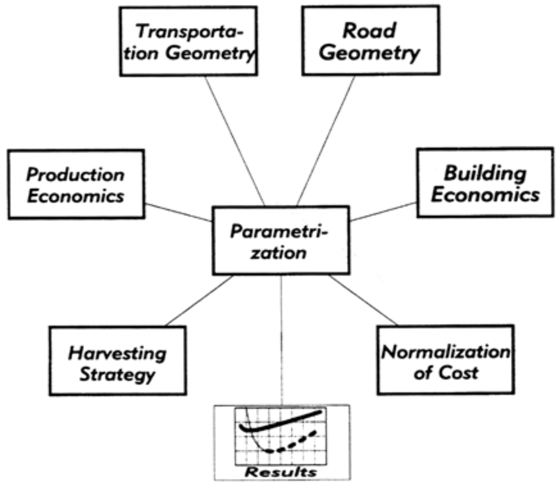

Fig. 2 Conceptual framework of the model. Modularization allows to handle complexity and flexibility to make modifications easily.

harvesting intensity and magnitude. "Cost normalization" considers the dynamic effects of project cash flow by converting them to a common measure.

3 Model analysis

Model analysis aims to describe the conceptual model of Fig. 2 *via* mathematical equations. As far as possible analysis is based on physical principles, whereas economical relationships may only be represented using empirical relationships.

1) Transportation geometry

$$RD \cdot s_0 = 1 \tag{1}$$

where RD, road density ($\text{m} \cdot \text{m}^{-2}$); s_0, road spacing distance (m).

It is quite common to use m per ha as a road density measure. In this case the right side of formula (1) will take the value of 10,000. The above relationship is only valid if the following assumptions are fulfilled: roads are straight lines in a horizontal plane; they are laid out parallel with regular spacing s_0; To describe road networks with intersects and irregular spacing Segebaden (1964) introduced a network correction factor c_{net} that may be calculated for geometrical networks, and that can be estimated by a sampling system for any shape of road networks and road segment. He demonstrated that c_{net} is equal to 1 for even spaced roads of infinite length, and takes the value of 2 for a stochastic layout of lines in the plane. Several researchers estimated the network correction factor for real conditions using a sampling system (*i.e.*, Segebaden, 1964; Abegg, 1978) that is very close to the approximation procedure suggested by Suddarth and Herrick (1964). For alpine conditions in Central Europe c_{net} usually lies between 1.3 and 1.8.

$$s_0 = \frac{1}{RD} \cdot c_{\text{net}} \tag{2}$$

where c_{net}, network correction (factor).

Equations (1) and (2) are only valid in a two-dimensional, horizontal plane. In mountain conditions sloped terrain dominates, and the basic assumptions of the above relationships are not adequate. We need to include a third dimension to get a satisfactory representation of the real world conditions. It seems to make sense to enlarge relationship (2) by adding a further correction factor that represents the functional relationship between road spacing in the horizontal plane and the corresponding slope distances. Off-road transportation of timber is measured by real distances along the path of movement. A three-dimensional straight line road segment L (Fig. 1) is defined by the x-, y-, and z- components of a rectangular coordinate system. Road spacing s_0 can be written as a function of L_x, L_y, and L_0 (3).

$$s_0 = \frac{L_x \cdot L_y}{L_0} \tag{3}$$

where L_x, x-component of road segment (m); L_y, y-component of road segment (m); L_0, horizontal length of road segment (m).

Road spacing s_{slope} in the inclined plane should be expressed by x-, y-, and z-components of the road segment. Additional parameters are the ground slope η and the maximum allowable gradient of the road v. s_{slope} is the height of the triangle $L - L_x - (L_y/\cos\eta)$. The first and the second term of Eq. (4) represent the area of the mentioned triangle whereas the third term represents the reciprocal of the baseline.

$$s_{\text{slope}} = \frac{L_y \cdot L_x}{\cos\eta} \cdot \frac{\cos v}{L_0} \quad (v < \eta) \tag{4}$$

where v, maximum allowable road gradient (°); η, ground slope (°).

The slope correction factor c_{slope} is the quotient of s_{slope} (3) and s_0 (3). Equation (5) is only valid when the ground slope is greater than the maximum gradient of the road ($v < \eta$). In all other cases it will take the value of 1.

$$c_{\text{slope}} = \frac{s_{\text{slope}}}{s_0} = \frac{L_y \cdot L_x \cdot \cos v}{\cos\eta \cdot L_0} \cdot \frac{L_0}{L_x \cdot L_y} = \frac{\cos v}{\cos\eta} \quad (v < \eta) \tag{5}$$

Using the slope correction factor c_{slope} Eq. (2) may be rewritten as follows:

$$s_{\text{slope}} = \frac{1}{RD} \cdot c_{\text{net}} \cdot c_{\text{slope}} \tag{6}$$

where s_{slope}, road spacing, measured in the inclined plane (m); c_{slope}, slope correction (factor).

s_{slope} is the deciding parameter for off-road transportation. If cable systems are used to transport the timber between roads, then the maximum available skyline length will limit the allowable road spacing (s_{slope}). In many optimization models of road density a basic assumption is that off-road movement of timber occurs on a right-angled straight line to the roadside. In reality the angle between road an off-road path is often acute, and the path is wind. To include this fact, Segebaden (1964) introduced another factor into his model (2) that calculates the length of the off-road transportation path. Equation (6) therefore has to be enlarged by another factor

c_{offr}. that is also called factor of sinuosity (Lussier and Tardiff, 1964).

$$l_{offr} = \frac{1}{RD} \cdot c_{net} \cdot c_{slope} \cdot c_{offr} \quad (7)$$

where l_{offr}, length of second order transportation line (m); c_{offr}, off-road path correction (factor).

Segebaden (1964) introduced the factor c_{offr} in the horizontal x–y plane for two dimensional problems. Optimal transportation requires that the different classes of transportation lines are perpendicular. Increasing slope angles reduce the angle of intersection between the two classes of transportation lines and therefore enlarge the off-road transportation distance. To analyze this effect we first need to calculate the angles β and β′ respectively (Fig. 1) located in the inclined plane. L is the hypotenuse of a right-angled triangle whereas $L_y/\cos\eta$ is a leg. The quotient is the sinus of angle β and can be calculated as follows.

$$\beta = \arcsin\left[\frac{\tan v \cdot \cos v}{\tan\eta \cdot \cos\eta}\right] \quad (v < \eta) \quad (8)$$

The layout of first and second order transportation lines is optimal if they are perpendicular. Using Eq. (8) we can first calculate β and then β′ for second order transportation lines (*i.e.*, cable roads, skid roads). As long as the sum $\beta + \beta' >= 90°$ we are free to choose a perpendicular line system. When $\beta + \beta'$ becomes smaller than 90° the length of the off-road transportation line has to be calculated using Eq. (7). We now need to calculate the correction factor c_{offr}.

$$c_{offr} = \frac{1}{\sin(\beta + \beta')} \quad [(\beta + \beta') < 90°] \quad (9)$$

where β, inclined angle between contour line and (°) first order transportation line (road); β′, inclined angle between contour line and (°) second order transportation line (skid road).

Inserting Eq. (9) into function (7) allows the calculation of the inclined length l_{offr} of the off-road transportation line.

The two categories of lines intersect. The reference area is defined by a parallelogram built by road spacing distance s_0 and the spacing of the second order transportation lines d_0. The reference area covering one cell can be expressed as follows:

$$A_{ref} = \frac{d_0 \cdot c_{net}}{RD \cdot \sin(\beta + \beta')} \quad [(\beta + \beta') < 90°] \quad (10)$$

where A_{ref}, area of one cell (m^2); d_0, spacing of second order transportation lines (m); c_{net}, network correction (factor); RD, road density (m·m^{-2}); (β + β′), angle between first and second order (°, < 90°) transportation lines.

2) Road geometry

Equations (1) to (10) describe the relationship of road network density and the relevant variables of off-road transportation. They are just one part of road network engineering. Feasibility highly depends on the question if geotechnical design allows a safe and reliable construction of all the components of the road structure (embankment, pavement, drainage, earth retaining structures). To judge feasibility and the degree of difficulty a cross-section model of the road to be built is analyzed (Fig. 3).

Cut slope area A_{cut} is a good indicator to quantify the construction difficulty and praide a cost estimate. We therefore need to derive a functional relationship between excavation volume, ground slope, and geometrical properties of the geotechnical structure of the road.

We base our analysis on equations of the relevant straight lines (cut slope, fill slope, ground slope), and afterwards look for a balance of cut and fill volume. The shifting distance s found for the volume balance will allow the calculation of the excavation volume measured in m^3·m^{-1}.

$$z = y \cdot \tan\varphi_{cut} + s \cdot \tan\varphi_{cut} \quad (11)$$

where s, shift distance (m); tan φ_{cut}, cut slope ratio (factor, *e.g.*, 1:1).

$$z = y \cdot \tan\varphi_{fill} + (w - s) \cdot \tan\varphi_{fill} \quad (12)$$

where w, with of road shoulder (m); tan φ_{fill}, cut slope ration (factor, *e.g.*, 4:5).

$$z = \tan\eta \quad (13)$$

where tan η, ground slope (factor in %).

Using Eqs. (11) to (13) allows to calculate the cut area A_{cut} (14) and the fill area A_{fill} (15) as a funtion of the geometric properties of the cross-section.

$$A_{cut} = \frac{s^2 \cdot \tan\varphi_{cut} \cdot \tan\eta}{(\tan\eta - \tan\varphi_{cut}) \cdot 2} \quad (14)$$

$$A_{fill} = \frac{(w - s)^2 \cdot \tan\varphi_{fill} \cdot \tan\eta}{(\tan\eta - \tan\varphi_{fill}) \cdot 2} \quad (15)$$

Functions (14) and (15) are solved to find the balance of the cut and fill areas. During construction work a portion of the fill volume is usually lost by shrinking what is compensated by a factor f_{shr}.

$$\frac{s^2}{(w - s)^2} = \frac{\tan\varphi_{fill} \cdot \tan\eta \cdot (\tan\eta - \tan\varphi_{cut}) \cdot 2 f_{shr}}{(\tan\eta - \tan\varphi_{fill}) \cdot \tan\varphi_{cut} \cdot \tan\eta \cdot 2} = F \quad (16)$$

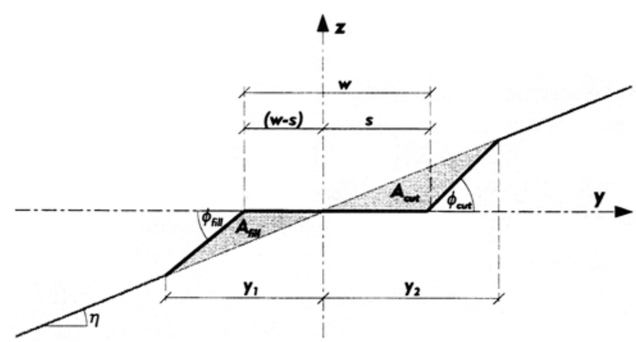

Fig. 3 Structural model of road cross-section. Geotechnical engineering deals with three system components: (1) embankment, (2) pavement, and (3) earth-retaining structures.

Equation (16) is quadratic and may be soved as follows.

$$s^2 \cdot (1-F) + s \cdot (2wF) - (w^2 F) = 0 \tag{17}$$

$$s = \frac{-2wF \pm \sqrt{4w^2F^2 + 4(1-F) \cdot w^2 F}}{(2-2F)} \tag{18}$$

There are two solutions for s. Only the positive value of the square root term makes sense. Using s we can now calculate the cut area based on formula (14).

3) Production economics

The total cost function of the road spacing problem consists of different terms. Matthews (1942) distinguished road building cost and yarding cost as the two main components. Production cost can be classified into different categories:

- variable cost is a cost that varies directly with the level of output. Variable extraction cost may be expressed as a function of extraction distance and therefore of road density.
- Indirect cost is a cost needed to support the primary work task. It consists of transporting machines, workers *etc.* to a new work site, setting-up and taking-down the production system or moving from roadside to the stand.
- Fixed cost is a cost a firm would occur even if its output for the period in question were zero. Such costs are often called overhead cost (see Thompson, 1992).

The basic concept underlying variable cost is that of production functions. Variable cost may be calculated by dividing the system cost per unit of time by the system productivity per unit of time. Both system cost and system productivity are technology dependent, and may only be estimated for given technologies. In the following analysis we will focus on two families of technology applicable on slopes, cable skidders and tower yarders.

Variable cost for skidder extraction is calculated using the productivity model presented by Abegg (1980). The original model is presented in graphical form using five time elements and a load volume estimator. Three basic variables are needed: the lateral yarding distance, the skidding distance covered on the skid road, and the mean volume per log. Equation (19) combines the input variables and the road geometry functions (7) and (10) respectively.

$$CP_{\text{skid}} = \frac{SC_{\text{skid}}}{f\left(\frac{l_{\text{offr}}}{2}, \frac{d_0}{4}, pvol\right)} \tag{19}$$

where CP_{skid}, variable skidding cost (CHF·m^{-3}); SC_{skid}, skidder system cost (CHF·PSH^{-1}); $f(\cdots)$, productivity model (Abegg, 1980) (m^3·PSH^{-1}) ; $l_{\text{offr}}/2$, mean skidding distance, formula (7) (m); $d_0/4$, average lateral yarding distance, see (10) (m); *pvol*, mean volume per skidded log (m^3) ; *PSH*, Productive System Hour (h)

Frutig and Trümpy (1990) presented a productivity model for a typical class of tower yarders used in the European Alps. The parameters are the same as in Abegg's model. Additionally the yarding direction, uphill or downhill, is taken into account.

$$CP_{\text{yard}} = \frac{SC_{\text{yard}}}{f\left(\frac{l_{\text{offr}}}{2}, \frac{d_0}{4}, pvol, \text{dir}\right)} \tag{20}$$

where CP_{yard}, variable yarding cost (CHF·m^{-3}); SC_{yard}, yarding system cost (CHF·PSH^{-1}); $f(\cdots)$, productivity model (Frutig and Trümpy, 1990) (m^3·PSH^{-1}); $l_{\text{offr}}/2$, mean yarding distance, formula (7) (m); $d_0/4$, average lateral yarding distance, see (10) (m); *pvol*, mean volume per skidded log (m^3); *dir*, yarding direction (boolean); *PSH*, Productive System Hour (h).

In cable yarding operations indirect cost play an important role. The time used to set-up and take-down is about 30% of the scheduled time in selective logging operations customary in the European Alps. For skidder operations indirect cost is often a constant amount of time used to transport the production system to a new work site and to prepare the system for operational use.

$$CI_{\text{skid}} = \frac{cp_{\text{skid}} \cdot SI_{\text{skid}}}{A_{\text{ref}}} \tag{21}$$

where CI_{skid}, indirect skidding cost (CHF·m^{-2}); cp_{skid}, time to prepare the system per unit (ISH); SI_{skid}, indirect skidding system cost (CHF·ISH^{-1}); A_{ref}, Reference area, see (10) (m^2); *ISH*, Indirect System Hours (h).

For cable yarding operations set-up and take-down depends on the yarding system, the length of the cable road, the direction of yarding, and the terrain conditions. There are only few investigations quantifying such relationships. Frutig and Trümpy (1990) give figures for the estimation of indirect yarding time that are used in function (22).

$$CI_{\text{yard}} = \frac{f(l_{\text{offr}}, \text{dir}) \cdot SI_{\text{yard}}}{A_{\text{ref}}} \tag{22}$$

where CI_{yard}, indirect yarding cost (CHF·m^{-2}); $f(l_{\text{offr}}, \text{dir})$, time to set-up and take-down the system (ISH) per setting, model of Frutig/Trümpy; SI_{yard}, indirect yarding system cost (CHF·ISH^{-1}); A_{ref}, Reference area, see (10) (m^2); *ISH*, Indirect System Hours (h); l_{offr}, mean length of cable road, formula (7) (m).

Abegg (1978, 1988) investigated other indirect costs such as cost for the workers to move from roadside to the stand and back. Under European conditions overhead costs are included in the system cost per unit of time. In the present study only indirect cost CI_{skid} (21) and CI_{yard} (22) are taken into account.

4) Building economics

The most obvious cost that varies with road density is the cost of building roads. Most previous work to estimate cost of forest roads was based on expert opinions or empirical investigation (*i.e.*, Abegg, 1988). One basic assumption in most road spacing models is that road building cost per unit of length is constant and road cost highly depend on ground slope and on soil bearing capacity (Abegg, 1988). A cost estimating model therefore should be able to quantify the influence of the factors slope and ground conditions. Construction industry is making efforts to improve cost estimating and calculating. One promising approach is the "cost classification by elements CCE" framework (CRB, 1991). It is a hierarchical system based on elements, element groups, and macro-elements. The following analysis aims to describe the reference quantities on the element group level. According to CRB (1991) four element groups play a leading role for road constructions (Table 1): (1) embankment structures *F*, (2) retaining and supporting structures *H*, (3) drainage structures *K*, and (4) pavement structures *N*. Element groups *H*, *K*, and *N* may be estimated per unit of road length while element group *F* "embankment" highly depend on ground slope. We need to know life cycle cost estimates for road as well as for skid road construction and maintenance. Cost estimates first determine the quantities for each element group (Table 1). Then unit rates have to be estimated. Unit rates are usually based on experience, determined on the basis of proposals, contracts or completed projects. They are influenced by supply and demand and vary over time. Table 2 gives the cost elements used to find investment cost I and maintenance Cost C. Skid roads are earth roads of lower standards why retaining, supporting, and pavement structures are usually not used. Periodic maintenance includes reshaping of the road profile that usually occurs before a harvesting operation takes place. Truck roads on the other hand have a higher standard. Drainage as well as pavement structures are used to attain durability and security. Optimal maintenance strategies imply routine as well as periodic maintenance measures. Formula (23) makes it possible to estimate the road building cost as a function of the slope grade.

$$I = A_{\mathrm{cut}} \cdot c_{\mathrm{exc}} + c_{\mathrm{drain}} + c_{\mathrm{pav}} \tag{23}$$

where I, investment cost (CHF·m^{-1}); A_{cut}, cut area, formulas (14, 18) (m^3·m^{-1}); c_{exc}, excavation cost (CHF·m^{-3}); c_{drain}, cost of drainage structures (CHF·m^{-1}); c_{pav}, cost of pavement structures (CHF·m^{-1}).

Table 1 Element groups used for cost estimation. After CRB (1991).

Element group	Indication	Element group quantity	unit
F	Embankment structure	Excavation volume	m^3
H	Retaining and supporting structures	Surface of walls, and supporting structures	m^2
K	Drainage structures	Length of drains and sewers	m
N	Pavement structures	Road surface	m^2

Table 2 Element groups considered in estimating life-cycle cost of truck and skid roads. Ignoring retaining and supporting structures result in underestimating construction cost in very difficult terrain.

Element group	truck road	skid road
F Embankment	x	x
H Retaining and supporting structures		
K Drainage structures	x	(x)
N Pavement structures	x	
Routine maintenance	x	
Periodic maintenance	x	(x)

Maintenance costs are estimated using lump sum values. Routine maintenance is calculated on an annually basis using (24). c_{rout} is a constant that takes the value of zero for skid roads.

$$C_{\mathrm{r}} = c_{\mathrm{rout}} \tag{24}$$

where C_{r}, routine maintenance cost (CHF·m^{-1}·a^{-1}); c_{rout}, cost of routine maintenance (CHF·m^{-1}·a^{-1}).

$$C_{\mathrm{p}} = c_{\mathrm{per}} \tag{25}$$

where C_{p}, periodic maintenance cost (CHF·m^{-1}·n^{-1}); c_{per}, cost of routine maintenance (CHF·m^{-1}·n^{-1}).

Abegg (1988) investigated maintenance costs for conditions in the Swiss Alps. He found that routine maintenance costs for truck roads rise with increasing slope gradient and decreasing soil bearing capacity. Abegg also compared the periodic maintenance costs of truck and skid roads. Although his results are based on several assumptions, he recommended that periodic maintenance cost were 20 to 30% of the corresponding cost for truck roads.

5) Harvesting strategy

Harvesting strategy strongly influences the total cost function of road network optimization. The present study uses a life-cycle approach widely accepted in managed forests under European conditions. Over a whole life-cycle of a stand several harvesting interventions will take place. The pattern of cutting units as well as their shape varies in time which is why a road network optimization approach based on fixed cutting units is not adequate. Harvesting interventions are characterized by frequency and magnitude of operations. The integration of frequency times magnitude has to fulfill the sustained yield potential of the natural conditions of a specific location (26).

$$t_{\mathrm{ret}} = \frac{vol_{\mathrm{harv}}}{vol_{\mathrm{yield}}} \tag{26}$$

where t_{ret}, return period between harvesting interventions (a); vol_{harv}, timber volume extracted per harvesting (m^3·ha^{-1}) intervention (magnitude); vol_{yield}, sustained yield potential of a specific site (m^3·ha^{-1}·a^{-1}).

For selective logging operations under conditions in the Swiss Alps the harvesting magnitude is usually between 60 and 90 m^3·ha^{-1}. Assuming that the sustained yield potential is around 6 m^3·ha^{-1}·a^{-1} the resulting return period is between ten and fifteen years. Enlarging harvesting magnitude will increase the return period. The harvesting strategy presented differs fundamentally from strategies used in unmanaged forests and in clear-cutting regimes and therefore will also influence the result of road-network optimization.

6) Normalization of cost

Optimization is based on a total cost function that consists of (1) life-cycle cost of road construction and maintenance, (2) direct production cost, and (3) indirect production cost. To make the different cost elements comparable we need to normalize them in time and in reference unit. This process of normalization needs two kinds of transformations:

- The time value of money requires the transformation to a common measure. Widely used measures are the net present value NV, the annual equivalent AE, and the internal rate of return IRR (see *i.e.*, Park and Sharp-Bette, 1990). Forestry units on an annual basis such as yield ($m^3 \cdot ha^{-1}$) and harvesting intensity ($m^3 \cdot ha^{-1}$) are very common. We will therefore transform all investment and maintenance costs of roads to annual equivalents AE.
- Forestry aims to produce goods and services. A physical measure should build the base for cost units. There are two possibilities of cost units, a standard volume unit of the wood to be produced (usually m^3), and a standard area unit (usually ha). The Anglo-American community seems to prefer volume as cost unit (Thompson, 1992; Howard and Tanz, 1990; Peters, 1990, 1978; Bowman and Hessler, 1983) whereas the European researchers prefer area as reference unit (Sanktjohanser, 1971; Abegg, 1978, 1988).

Equation (27) calculates the annual equivalent AE of investment cost of roads.

$$\mathrm{AE}(i,n) = \mathrm{PV} \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \qquad (27)$$

where AE, annual equivalent (CHF); PV, net present value (CHF); i, interest rate (fraction); N, project life cycle (a); l, length of interest period, usually annually (a); n, number of interest periods (N/l).

A special problem is converting cost that arises in periods longer than one year such as cost of periodic road maintenance. We first have to calculate the net present value PV resolving (27) to PV and then multiply it by the capital recovery factor of (27). The interest rate is a factor of growth defined for the period of one year. For interest periods longer than one year we have to calculate the capital growth factor for this specific period using the term $(1+i)^l - 1$. Using the modified interest rate i' and the number of interest periods n' we can then calculate the net present value PV (28). The annual equivalent is afterwards determined using (26).

$$\mathrm{PV}(i',n') = C_\mathrm{p} \cdot \frac{(1+i')^{n'} - 1}{(1+i')^{n'} \cdot i'} \qquad (28)$$

where PV, net present value (CHF); i', modified interest rate ($(1+i)^l - 1$); n' number of interest periods (N/l); C_p, Cost at the end of each interst period ($\mathrm{CHF \cdot m^{-1}}$)

The total cost function (29) used for optimization is based on normalized cost with dimension $\mathrm{CHF \cdot ha^{-1} \cdot a^{-1}}$.

$$N_\mathrm{tot} = \left[\mathrm{AE}(i,n) \cdot I + C_\mathrm{r} + \mathrm{AE}[i,n,\mathrm{PV}(i',n')] \cdot C_\mathrm{p}\right] \cdot RD + CP \cdot vol_\mathrm{yield} + CI \cdot \frac{vol_\mathrm{yield}}{vol_\mathrm{harv}} \qquad (29)$$

where N_tot, total cost ($\mathrm{CHF \cdot ha^{-1} \cdot a^{-1}}$); I, investment cost of roads (23) ($\mathrm{CHF \cdot m^{-1}}$); C_r, routine maintenance cost (24) ($\mathrm{CHF \cdot m^{-1} \cdot a^{-1}}$); C_p, perodic maintenance cost (25) ($\mathrm{CHF \cdot m^{-1} \cdot l^{-1}}$); RD, road density ($\mathrm{m \cdot m^{-2}}$); AE(i, n), capital recovery factor (27) (factor); PV(i', n'), present-amount factor (28) (factor); CP, variable extracting cost (19, 20) ($\mathrm{CHF \cdot m^{-3}}$); CI, indirect production cost (21, 22) ($\mathrm{CHF \cdot m^{-2}}$); vol_yield, sustained yield potential of a specific site ($\mathrm{m^3 \cdot ha^{-1} \cdot a^{-1}}$); vol_harv, timber volume extracted per harvesting ($\mathrm{m^3 \cdot ha^{-1}}$) intervention (magnitude).

4 Implementation

Quantification of the total cost function needs to specify more than 25 variables. The use of the optimization model should be easy and applicable to specific conditions. It is therefore desirable to develop a computer program based solution. Most previous work done in this field use standalone computer programs depending on operation system and hardware platform. Another approach is to implement the model as an add-in application using standard business software. In the present study we implemented it as an add-in application for Microsoft EXCEL spreadsheet software using Visual Basic, allowing graphical output to be produced easily. According to the model structure (Fig. 2) the code was organized in modules implementing the above equations as Visual Basic functions.

Model Evaluation - Case Application

The usefulness of the above model shall be evaluated to differentiate skidder-based and yarder-based extraction concepts. A first step in model application is to parametrize the total cost function (29) to get numerical values. Table 3 gives the parameters used in the following model application.

Figure 4 shows cost functions for the two extraction systems as a function of road density, using 30% ground slope and 60% ground slope respectively. Abegg (1988) used the difference between cost at optimal road density to decide

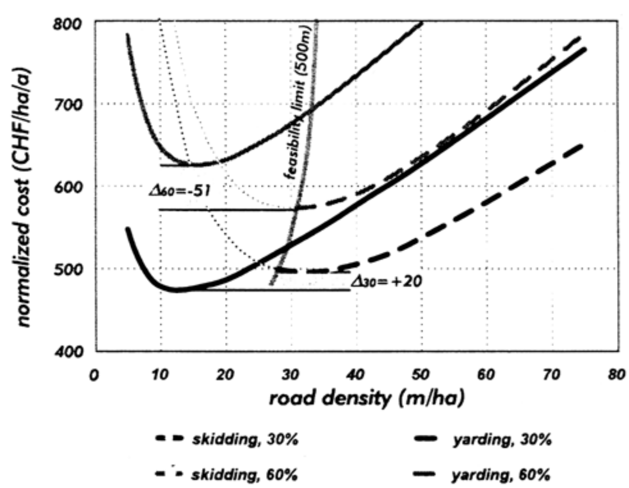

Fig. 4 Normalized cost as a function of road density and slope gradient for skidder- and yarder-based extraction systems. Above 42% the model prefers cable-based extraction systems, for the underlying parameters given in Table 3. Feasibility of yarder based extraction is limited to road densities approximately below 25 $\mathrm{m \cdot ha^{-1}}$ because of limited line length. Δ_{30}/Δ_{60} difference between total cost of skidder and cable-based extraction at optimal road spacing at 30% slope, and 60% slope respectively.

whether skidder or cable based extraction should be applied. In 60% ground slope conditions the model clearly favourizes cable-based extraction whereas ground-based system is preferred on 30% slopes. The point of inflexion lies at 42% ground slope where both optimal cost levels are equal. Another interesting finding is the increase of normalized cost with increased ground slope. Using a skid-road system rises the cost level by 30% if the ground slope increases from 30% to 60%. The corresponding increase is only 16% for yarder-based extraction.

Since the above findings are only valid for the parametrization of Table 3, a sensitivity study was carried out. The mean volume per log extracted has the biggest influence on the results of the model. Smaller piece volumes prefer the cable-yarder concepts whereas larger piece-volumes favourize skidder extraction. These findings heavily depend on the productivity models which are only valid for the specific technology from which the empirical relationships were derived. Technological advance could probably change this finding which is why it has to be used with care. Other important factors are the magnitude of harvesting intervention, the sustained yield potential, and the cost of road building. Increasing these factors lowers the ground slope limit that prefers cable-yarder based extraction concepts to about 35 % ground slope. Decreasing these factors puts the ground slope limit up to about 50%.

Discussion

The present study aims to develop an analytical road spacing model for steep slopes which differentiates ground-based and cable-based extraction concepts.

A new 3-dimensional road network model is developed extending the state-of-the-art of Segebaden (1964) by introducing a slope correction factor. It allows the consideration of the non-perpendicular intersection of first and second order transportation lines as a function of slope and maximum road gradient. Abegg's (1988) study gave some empirical relationships that did not explain the influence of changing maximum road gradients. A second finding is a cost model for road building based on cross-section geometry and a methodology called cost classification by elements CCE (CRB, 1991). This cost model reproduces increasing cost with bigger ground slope. The comparison with Abegg's (1988) empirical cost data leads one to suppose that road building cost is underestimated at slope grades above 50%. A possible explanation is increasing rock excavation that is not considered in the present approach. Additionally, pavement costs heavily depend on soil bearing capacity that has not been considered either. A third finding is the total cost function allowing to differentiate skidder and cable-based extraction concepts. The difference between total cost of the two extraction approaches at optimum road density estimates the ground slope at which cable-based extraction is preferred. The corresponding turning-point is between 35% and 50% ground slope which is lower than the recommendations in text books and guidelines. The results depend heavily on the productivity models used as a basis. The models of Abegg (1980) and Frutig and Trümpy (1990) were the most recent studies avail-

Table 3 Parametrization of the model. The values represent typical conditions in the Swiss Alps.

Module	Parameter	Skidder-based extraction	Yarder-based extraction
Transportation geometry	Maximum gradient of truck road	12%	12%
	Maximum gradient of second order transportation line (skid road, cable road)	20%	60%
	Net work correction factor c_{net}	1.33	1.33
	Spacing of second order transportation lines	160 m	60 m
Road geometry	Shoulder width of truck road	4.5 m	4.5 m
	Cut slope ratio	1	1
	Fill slope ratio	0.8	0.8
	Shrinkage factor	1.3	1.3
Production economics	System cost for direct extraction work	125 CHF	265 CHF
	System cost for indirect extraction work	45 CHF	135 CHF
	Mean volume per log skidded	0.3 m^3	0.3 m^3
Building economics	Excavation cost	12 CHF·m^3	12 CHF·m^3
	Cost of drainage structures for truck road	25 CHF·m^{-1}	25 CHF·m^{-1}
	Cost of drainage structures for skid road	4 CHF·m^{-1}	
	Cost of pavement structures for truck roads	78 CHF·m^{-1}	78 CHF·m^{-1}
	Cost of shaping skid road surface	4 CHF·m^{-1}	
	Routine maintenance of truck road	1 CHF·m^{-1}·a^{-1}	1 CHF·m^{-1}·a^{-1}
	Periodic maintenance of truck roads	15 CHF·m^{-1}·l^{-1}	15 CHF·m^{-1}·l^{-1}
	Periodic maintenance of skid roads	3 CHF·m^{-1}·l^{-1}	
	Return period of periodic maintenance for truck roads	15 a	15 a
Harvesting strategy	Sustained yield potential of harvesting site	6 m^3·ha^{-1}·a^{-1}	6 m^3·ha^{-1}·a^{-1}
	Timber volume extracted per harvesting intervention	80 m^3·ha^{-1}	80 m^3·ha^{-1}
Normalization	Interest rate (rise in prices deducted)	2%	2%
	Project life	50 a	50 a

able, although they contain many generalisations.

The validation and refinement of the model must take place in future studies. The most critical need is to derive productivity models of state-of-the-art skidder and cable yarder systems to consider the effects of technological progress. Another improvement would be to refine the road cost model. Model verification needs the evaluation of harvesting situations under a wide variety of conditions.

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